

DISCUSSION

Can Water Cause Brittle Fracture Failures of Non-ceramic Insulators in the Absence of Electric Field

We welcome the opportunity to discuss this paper [1] in light of its importance to the electric power transmission. We would like the authors to respond to the following:

1. The IEEE Task Force on Brittle Fracture has published a paper recently [2]. This task force was composed of members from utilities, industry and academia. This paper was based on extensive survey of brittle fractures of non-ceramic insulators (NCI) experienced throughout the world (total about 107). The survey was performed by the Edison Electric Institute (for data within the US) and the CIGRE Working Group 22-03 (for information on a worldwide basis). It was reported that there were a total of 16 brittle fractures at voltages of 138 kV and lower. Four of these brittle fractures occurred on guy insulators used to support the structures. Two brittle fractures occurred at 15 kV. It is well known that the electrical stress seen at voltages below 138 kV is low and not a problem for normal insulator operation. NCI used at these voltages do not employ corona rings for electric stress control. The guy insulators do not normally see any electric stress, except under wet conditions and that too only momentarily. At a much higher voltage of 500 kV, there was one brittle fracture reported in the USA that originated in the end fitting connected to the tower (ground). More recently, there have been at least 3 brittle fractures at 230 kV that occurred in the ground end fitting within one month of installation. Corona discharge activity can practically be ruled out for the guy insulators and the 15 kV insulators. We have inspected the 230 kV insulators of the type that failed within one month for corona activity and found none even at the line end. Most of the insulators that have failed by brittle fracture have been in relatively clean locations where surface discharges (dry band arcing) are unlikely. The electric field in all of the above cases at the location of brittle fracture is either small or nonexistent. Therefore, acid generation from corona discharges originating from outside the insulator can be ruled out.

2. One of the factors that led to our hypothesis is the analysis of partial discharges inside voids and corona external to the fiberglass rod of the insulator. Based on our calculations [3–5] we reasoned that the magnitude of discharges and the time for which they are required to stay in the same location to create acidic species necessary to cause brittle fracture was quite severe and prolonged. Given the design and application details of non-ceramic insulators even at the highest voltage, this is not easily achievable in practice. Have the authors performed any calculations/experiments/field observations to establish that electrical discharges of the required magnitude and duration to create acids are possible?

3. Our experimental set-up and the one used by the authors are significantly different. Therefore we are not surprised that they were unable to reproduce the failures. We published photographs of samples that failed. Our criteria for calling them brittle fracture failures were consistent with IEEE and CIGRE publications [2, 6].

4. There is extensive literature which addresses the durability of E-glass composite materials [7–9]. The SCC mechanism by water may coexist with other mechanism, namely hydration, hydrolysis, and ion migration (selective ion leaching) [10]. The assumption that electrical discharge is a necessary component of the degradation mechanism cannot be validated due to the wealth of available literature pointing to the degradation of E-glass composites both in natural service loads, or under stress corrosion cracking [11–14]. The overall water/glass interaction may produce residual concentrations similar to those observed after acid attack. Chemical analysis may provide the final answer regarding the existence of the products, but estimating the origin of the attacking medium is not easily possible.

Liao et al. [15] showed that moisture-induced tensile stress on the fiber is substantial when the absorbed moisture level in the polymer matrix is high. They concluded that moisture-induced tensile stress in glass fibers plays an important role in strength degradation of unidirectional composite under environmental aging. Nemat-Nasser and co-workers [16, 17] found that composites containing flaws subjected to adverse environmental conditions in the presence of a sustained load, may have reduced mechanical properties and changes in their microstructural properties up to failure. E-glass/vinyl ester composite coupons with a single edge flaw were conditioned for periods up to 7900 h at room temperature and at an elevated temperature, with and without a sustained load, to determine the changes in the tensile properties and damage mechanisms which occur with the introduction of the flaw. The early damage mechanisms were found to change from transverse matrix cracking, fiber cracking, and occasional edge delaminations for unnotched specimens to the growth of a significant matrix crack from the notch tip and well-defined longitudinal tow debonding for notched specimens. This mechanism is quite similar to the embrittlement effect that we proposed [18].

Tests of Kajorncheappunngam et al. [14] indicate that as much as 23% reduction in strength, and 26% reduction in strain capacity of E-glass epoxy composites were observed after five months of exposure to distilled water. Standard and low styrene emission glass fiber-reinforced unsaturated polyester composites were aged by immersion under flexural and tension loads by Autran et al. [19]. Their results show that the application of

a mechanical load does not modify either the quantity of the absorbed water or the diffusion coefficients significantly. For an applied stress of less than 10% of the fiber strength, the influence on aging is small, but for larger applied stresses, the rate of reduction in the mechanical properties is accelerated and, in some cases, premature rupture is observed.

5. Barbero et al. [20] present models to predict the time- and environment-dependent degradation of tensile strength of unidirectional E-glass fiber composites. While the model is phenomenological, it incorporates stress corrosion, zero-stress aging, interphase aging, and moisture-dependent matrix stiffness. They also introduce the concept of inert aged strength in order to incorporate data developed under different environmental exposure and load-testing conditions. The conditions for which exposure and aging affect the composite significantly are discussed and the model predictions are compared with available experimental data.

In consideration to the above referenced documents, the process of degradation of E-glass composites with certain flaws under high humidity conditions has been thoroughly documented.

Flexural test is perhaps the most common test conducted for a variety of materials including ceramics, composites, and both ductile and brittle materials. This is a simple test to set up and present the basic material property data. We believe that our test methodology for SCC using a flexural set up is a viable, economical, and easily conducted test to ascertain the response of rods subjected to sustained loading. There is no doubt that additional work is necessary before it can generate reproducible results among various testing laboratories.

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REPLY

This Reply is based on our experience gained when studying predominantly mechanical failure modes of composite (polymer, polymeric, non-ceramic) insulators [1, 21–56]. It should be pointed out that the research described in [1] was performed following the findings presented in [57] which was not referenced in the Discussion.

Our Reply follows the same item numbers used by the discussers.

1. The statement in item 1 of the Discussion that “More recently, there have been at least 3 brittle fractures at 230 kV that occurred in the ground end fitting within one month of installation” can be quite easily disputed considering the information provided in [44–46, 56]. We are fully aware of those failures, which recently happened in crimped insulators; one of them was analyzed in [44, 45, 56]. It should be mentioned here that crimping [18, 24, 27, 29, 34, 43–46] is presently the most widely used method of attaching the fittings to the glass reinforced polymer (GRP) rods. It has been shown in [44, 45], that

if overcrimping occurs the critical mechanical loads required to mechanically break the GRP rods in the insulators can be reduced so much with the amount of overcrimping that the insulators could actually mechanically fail in service under the weight of the line without any effects of the electric field.

In crimped insulators, catastrophic purely mechanical failures can occur either inside or just outside the fittings (either energized or un-energized) if the crimping deformations applied to the fittings were either excessive or improperly distributed [44–46, 56]. This type of failure, also associated with the formation of transverse cracks in the GRP rods, quite closely resembles classical brittle fracture on a macro-scale [45, 56]. In both cases, large transverse cracks running perpendicular to the rods were observed. However, when the fracture surfaces of the fibers were examined [44, 45, 56], it was noted that the classical mirror, mist and hackle zones [58, 59], typical for the fibers that failed by stress corrosion cracking (SCC) [1, 22, 25, 33, 37–44, 47–50, 55, 58–60] and brittle fracture [1–3, 21–23, 25, 28, 31, 32, 35, 36, 43, 44, 52, 54–57] were actually missing in the fibers, which failed due to the combined effects of overcrimping and external loads. The close macroscopic resemblance of the failures by brittle fracture and overcrimping renders both failures to be incorrectly classified. This means that the mere fact that someone reported a “brittle fracture” should not be immediately taken as a legitimate scientifically documented piece of information. Very detailed macroscopic, microscopic and chemical analyses [2, 22, 25, 28, 35, 43, 44, 52, 56] of a field-failed insulator are required to be absolutely sure that brittle fracture actually occurred. It is most doubtful that all the brittle fracture failures reported in the Task Force report [2] were subjected to these types of analyses. Even in [57] no chemical analysis of the composite guide was performed the way it was done, for example, in [52].

Regarding the comment on guy insulators, one of them was analyzed in [52] and our detailed response to this particular comment can also be found in [52]. Concerning the 500 kV insulator, which apparently failed by brittle fracture, the comments about the effect of overcrimping and the necessity of performing very detailed chemical analyses also apply here. It should be stated however that the electric field concentration at the ground end of a 500 kV insulator could be high enough to cause brittle fracture if the brittle fracture model discussed in the next section is considered. Even, then, a detailed chemical analysis of the insulator would have to be conducted to classify the failure as brittle fracture. Considering all of the above, we cannot accept the observation and conclusions made in the Discussion that brittle fracture failures have occurred without any (or minimal) effect of the electric field and therefore “acid generation corona discharges originating from outside the insulator can be ruled out”.

2. It has been shown that the surfaces of composite insulators near the energized ends can be heavily contaminated by nitric acid (nitrates) [61], which can be formed by water droplet coronas [62]. Therefore, the fact that nitric acid can be formed externally on the surfaces of the insulators should not be disputed. Regarding the comment that nitric acid could not easily be

formed internally, the data reported in [3] and [57] must be carefully analyzed. It was also reported in [57] that when GRP rods were exposed to water and mechanical stress, “cracking”, “slight cracking” and “severe delamination” were observed in the composites. At the same time, in [3] statements were made that “Defects in the form of voids, micro-cracks, capillarities can exist in the GRP rods used in NCI. It is important to note that the size of these defects are normally small”. Therefore, “acid generation due to partial discharges (PD) in the GRP rods can be eliminated as the reason for brittle fracture” [3]. It can be seen that no connection was made by the authors of the Discussion that if water ingress is allowed into the fittings of the insulators in-service, the water will generate “severe delamination” inside the GRP rods in the areas exposed to water and mechanical stresses and that the electric field distribution near the energized end fitting will dramatically change [22, 26, 30, 43].

In our brittle fracture model [1, 21–23, 25, 28, 31, 32, 35, 43, 44, 52, 51, 54–56] recently verified in an actual failed NCI [52], water ingress into the insulators creates “severe delamination” in the GRP rods at the rubber housing/GRP rod interface, which is the first region of the composite rod affected by water ingress. These cracks are normally large and can be observed in some cases with the naked eye [21, 22]. To support the model we performed electric field calculations [22, 26, 30, 43] in order to demonstrate the possibility of PD that is necessary to create nitric acid in service inside large “severe delamination”, axial splits and other cracks that are always associated with the brittle fracture process. The calculations were initially conducted by N. Fujimoto and J. M. Braun of Ontario Hydro, Canada as part of our DOE/EPRI project [22, 26], and then in Denver [30, 43]. It has been shown in [22, 26, 30, 43] that if the cracks are partially filled with water, the field concentration is high enough to initiate PD inside the insulators in-service and that the production of the nitrogenous species can be considered significant [52]. Therefore, we respectfully disagree with the hypothesis presented in the Discussion and in [3]. We also would like to emphasize that what was proposed in [3] and in the Discussion is in total contradiction to what we have been proposing since 1994.

3. In this part of the Discussion the authors stated that they were not surprised that we could not have reproduced their results since two different set-ups were used in our work [1] and theirs (since they did not reference [57] in the Discussion we have to assume that this is the source to which they referred). However, we are most surprised. There are always differences between different laboratories that cause minor variations in the measured material property. In this case, however, the difference was enormous; brittle fracture in water reported by the authors of the Discussion in their previous work and no brittle fracture at all in [1] using the same composites that were tested in the same chemical environment. Surely, this cannot be blamed on the difference in the testing setups. The techniques developed over the years to monitor the initiation [37, 38, 41–44, 47–49] and propagation [22, 23, 25, 36–40, 54, 55, 58–60] of SCC and brittle fracture in insulator composites are quite refined and we have monitored our composites for the

failure of individual fibers and not for the macro-failures such as large cracks or broken rods. Using our monitoring techniques we have performed controlled stress corrosion tests [1] with exactly the same ultra pure water and the same insulator GRP composites as used and tested by the authors of the Discussion; and nothing happened [1].

We agree, however, that our setup [1] was different from the setup used by the authors of the Discussion and that we should have used the same setup with exactly the same testing conditions. The problem was that we were prevented from doing this because in [57] the authors unfortunately did not report on their testing conditions. It can be easily observed by examining [57] that it would be impossible to reproduce their findings since the mechanical loads, so critical in the stress corrosion cracking of unidirectional glass polymer composites, were not given. Also, the actual testing arrangement was not described in sufficient details. The dimensions and descriptions of supports and loading conditions were not reported in [57]. This makes it impossible to reproduce the results of the authors of the Discussion under exactly the same testing conditions.

4. The facts presented in [4–20] that water will have damaging effects on glass fiber polymer composites are difficult to dispute. These facts have been known since the 1960s. We fully agree that if exposed to water, glass/polymer composites will gradually deteriorate and gradually lose their strengths especially under very long exposure times at elevated temperatures. Water will degrade these composites by generating interfacial failures, cracks in the matrix, even occasional fiber fractures. These facts were not disputed in [1]. What we disputed in [1] are the statements that “the failure of in-service NCI in the brittle fracture mode can occur under the influence of water and mechanical stresses” and that “the failure is more likely to happen with water than with acids” [57].

In SCC (and brittle fracture) under low tensile loads, the failure of the glass/polymer interfaces, fiber pullouts, delamination and debondings are significantly suppressed, and the process is dominated by the sequential failure of the fibers followed by the immediate fracture of the surrounding matrix along transverse macroscopic fracture surfaces [22, 25, 33, 37–44, 47–50, 55, 58–60]. Contrary to SCC, which is a fiber dominated process (sequential fiber fractures), the damage to the composites caused by water is an interface and matrix dominated process (debonding, delamination, matrix cracking) [4–20, 22, 53]. This makes the formation of transverse macroscopic fracture surfaces in the composites exposed to water impossible exactly as our experiments have shown in [1].

5. Again, we do not dispute that “the process of degradation of E-glass composites with certain flaws under high humidity conditions” can occur. We fully agree that these composites will degrade under high humidity conditions with time and that the degradation rate will depend on the moisture content, temperature, polymer type, etc. [4–20, 53]. However, the process will be gradual and these composites will not fail in half by brittle fracture in the direction perpendicular to the fibers in short periods of time [57].

With respect to the accuracy of the four point bending test used by the authors of the Discussion in the past [57], several critical comments must be made in response to the last point of item 5. The claim that “Flexural test is perhaps the most common test conducted for a variety of materials including ceramics, composites, and both ductile and brittle materials” is incorrect when applied for testing rods. The authors should have provided references to support their statement. However, we are not aware of any published sources, which could support this statement. It is also claimed in the Discussion that GRP rods can be subjected to four point bending to “ascertain the response of [the] rods subjected to sustain loading”. However, the GRP rods used in composite insulators are not subjected to four-point bending in-service; they are subjected to tension, compression, torsion and cantilever loads either separately or in combinations. Besides, it is practically impossible to bend a GRP rod by four-point bending without introducing other stresses such as shear. In addition, the only pure tension region (theoretically) in a rod subjected to bending is a line in the top-most region of the rod. Only along this line away from the loading/support points is the stress uniform and close to pure tension. However, on both sides of this line, the stress fields are very complex and multiaxial including shear.

When describing SCC (or brittle fracture) we always make references to the amount of tensile stress at which the fracture initiated and propagated [1, 38–44, 47–50, 58–60]. Therefore, the best mechanical test to simulate experimentally this type of fracture should be a purely tensile test. If other stresses are present (hoop, compression, shear, combined), they should be eliminated, if possible, or significantly reduced, or at least accounted for. Moreover, if the GRP rod in the test under discussion is supported by sharp supports positioned very close to the water/acid tank and to the gage section of the specimen, extremely undesirable effects could be introduced such as: (1) high multiaxial stress concentrations in the GRP rods inside their gage sections and (2) initial intralaminar purely mechanical damage in the gage sections of the GRP specimens. These effects could greatly affect the failure process and the final outcomes of the tests especially if the applied loads were high. In particular, they could affect the loads at failure and the location of failure, which should always occur in the specimen gage sections away from the loading/supporting points. In conclusion, we agree that the test mentioned in the Discussion is “simple, economical, and easy to conduct”. At the same time, we entirely disagree that the test is accurate and suitable for the stress corrosion testing of composite insulators.

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